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The goal of this research program is to develop an MBE system adapted to the growth and characterization of complex oxide films. Our research focus is on the epitaxial growth of complex oxides, such as $SrTiO3$ and $BaTiO3$, on single crystal silicon and complex oxide substrates. This task leads to a number of requirements for our system: 10000 C substrate temperature in order to remove Si02 from Si wafers in situ; angstrom per minute deposition rates to accurately synthesize unit cell buffer layers; high resolution reflection high energy electron diffraction (RHEED) to characterize surface structure; and an oil free pumping system to avoid contamination.

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Harold Weinstock, PhD, DHC, AFRL Fellow
AFOSR/NE
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August 28, 2003

Dear Harold,

Please find enclosed a progress report for AFOSR project F49620-01-1-0330 (Atomically Smooth Epitaxial Ferroelectric (Piezoelectric) Thin Films for the Development of a Nonvolatile, Ultrahigh Density, Fast, Low Voltage, Radiation-Hard Memory). The period covered is July, 2002-July, 2003, and the location of the project is Yale University. The PI and co-PI are Charles Ahn and T.P. Ma, respectively. Also enclosed is a report for AFOSR DURIP construction project F49620-02-1-0210 (Construction of a reactive co-evaporation oxide thin film deposition system). The project is located at Yale University, and the PI is Charles Ahn.

Sincerely,

Charles Ahn

Progress report for AFOSR project F49620-01-0330 (Atomically Smooth Epitaxial Ferroelectric (Piezoelectric) Thin Films for the Development of a Nonvolatile, Ultrahigh Density, Fast, Low Voltage, Radiation-Hard Memory), July, 2002-July, 2003

The goal of this research program is to develop a nanostructured medium that will serve as the building block for an ultrahigh density, nonvolatile memory. The device structure for the medium is a nonvolatile field effect transistor, with the colossal magnetoresistive (CMR) oxide $La_{1-x}Sr_xMnO_3$ (LSMO) as the channel material and the ferroelectric oxide $Pb(Zr_xTi_{1-x})O_3$ as the gate insulator. The conducting LSMO channel has a metallic density, which results in a depletion width smaller than 1 nm. This small depletion width allows one to potentially achieve atomic scale device dimensions, beyond the limit of scaled Si CMOS technology. We use the permanent, bi-stable polarization of PZT to modulate the carrier concentration and hence conductivity of LSMO, with the resulting high and low conductivity states representing the on and off states.

Using RF magnetron sputtering, we have grown single-crystal, epitaxial, PZT/LSMO heterostructures with high crystalline quality and atomically smooth surfaces. These heterostructures have been patterned into resistivity paths for transport measurements. Nonvolatile, reversible switching of the resistivity of the LSMO layer has been induced by applying voltage pulses of a few volts across the heterostructures. On/off ratios of ~100 have been achieved, and switching between metallic and insulating behavior has been induced in ultrathin LSMO films. Continuous stability tests have also been carried out on these field effect devices. The on and off states are stable over the period of ~1 week, the length of the measurements. Devices have also been measured after ~1 year, with stable on and off states, showing that the materials properties are robust.

We have also investigated how fast these devices can be switched. Voltage pulses with various pulse widths have been applied across the PZT layer, and the resulting conductivity changes have been measured. For large devices (typical dimensions of tens of microns), the switching time is on the order of several microseconds, consistent with the calculated RC time constant of the circuit. Smaller RC time constants can be achieved in the future by reducing the device dimensions. Using ferroelectric capacitor structures, which have smaller RC time constants, we have observed switching times of less than 10 nanoseconds. Cycling of the capacitors also shows that the ferroelectric maintains its polarization after 10^{10} switching cycles.

We are also examining how small these field effect structures can be made. The first step is to study the minimum domain size that can be achieved in a ferroelectric. Using an atomic force microscope equipped with a conducting tip to sense the piezoelectric response of the material, we have written and imaged ferroelectric domains with sizes as small as 40 nm. This corresponding areal density for this bit size is ~100 Gbit/in^2. Currently, the minimum domain size that can be achieved is limited by the radius of curvature of the AFM tip and the RC constant of the AFM.

Future research will involve reducing the minimum achievable domain size, examining new materials for field effects, fabricating field effect devices with optimized geometries, and achieving smaller RC time constants for these devices.

Report for AFOSR project F49620-02-1-0210 (Construction of a reactive co-evaporation oxide thin film deposition system).

The goal of this research program is to develop an MBE system adapted to the growth and characterization of complex oxide films. Our research focus is on the epitaxial growth of complex oxides, such as $SrTiO_3$ and $BaTiO_3$, on single crystal silicon and complex oxide substrates. This task leads to a number of requirements for our system: 1000° C substrate temperature in order to remove SiO_2 from Si wafers in situ; angstrom per minute deposition rates to accurately synthesize unit cell buffer layers; high resolution reflection high energy electron diffraction (RHEED) to characterize surface structure; and an oil free pumping system to avoid contamination.

We have constructed the system from individually selected components in order to tailor the system to these specific research goals and to streamline cost. Construction of the system is complete, and all components have been successfully tested. Using two UHV cryopumps (4000 L/sec and 2200 L/sec pumping speeds), a 100 L/min scroll roughing pump, and a 33 L/sec turbo-drag pump connected to the chamber, we have reached a base pressure of 10^{-9} Torr without baking the system. A procedure for baking the system has been established to achieve the lowest pressure possible without compromising system components.

The components tested and in operation include:

- Custom designed UHV vacuum chamber
- 2 effusions cells powered by 1 kW power supplies
- 20 keV RHEED gun
- CCD camera (with f0.95 lens) and framegrabber for RHEED image acquisition
- 3 inch SiC substrate heater powered by 3 kW supply
- 36 inch transfer arm and transfer procedure to sample heater
- 10 kW water re-circulator
- QCM deposition monitor
- Rate monitoring and effusion cell shutter control program
- Equipment protection interlock program.

A photograph of the vacuum chamber is on the next page: